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ATTITUDE DETERMINATION FOR TIROS SATELLITES

by

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SUMMARY

The Tiros satellites scan the earth's cloud cover by means of television, and observe its infrared albedo in several wavelength regions. The satellite is spin stabilized, but the spin axis direction varies in response to magnetic and gravitational torques. The recent Tiros satellites contain a variable intensity electromagnet to steer the satellite in orbit; and the satellite's attitude must be determined and predicted so that appropriate steering commands can be given. The basic data for determining the satellite attitude are obtained from the television pictures and from the infrared sensors themselves (the latter sense horizon transit times). These basic data are processed, edited, and analyzed, together with accurate orbital information, by means of attitude and orbit determination systems formulated and programmed for use in IBM 7094 computers. The pointing directions for the various cameras and sensors are determined, predicted, and programmed by means of these attitude determination systems.

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INTRODUCTION

The *T*elevision *I*nfra*r*ed *O*bservational *S*atellites, Tiros I, II, III, IV, V, and VI, are meteorological satellites designed to obtain television cloud data and reflected solar and earth radiation information. Tiros satellites photograph the earth's cloud cover by using television cameras and observe and record the reflection of solar radiation by the earth's surface and by clouds in a number of wavelength regions by means of sensors and magnetic tape recorders. The satellite is spin stabilized; however, the spin axis direction varies with time in response to magnetic and gravitational torques. The satellite's attitude or orientation as a function of time must be quickly and accurately determined and predicted for a number of reasons. The recent Tiros satellites contain a variable intensity electromagnet which can be commanded from the ground to steer the satellite in orbit.

In order to give the appropriate steering commands to achieve the various satellite objectives, the attitude of Tiros must be established and predicted. The spin axis direction with respect to the sun is important since it affects the solar energy reception rate, the temperature and the power supply. The directions in which the television cameras point must be predicted and controlled in order to take direct or remote cloud picture sequences that yield photographs of meteorological interest. This is particularly important in the four-fifths of the globe not covered by weather stations. The attitude of Tiros is also required to prepare radiation maps that show the earth distribution of various spectral bands.

TIROS III

The Tiros structures are 42 inches in diameter and 19 inches high. The infrared sensors are mounted at ninety degrees and at forty-five degrees to the satellite axis. The satellite spin rate of between 9 and 12 rpm can be maintained by firing pairs of peripheral rockets.

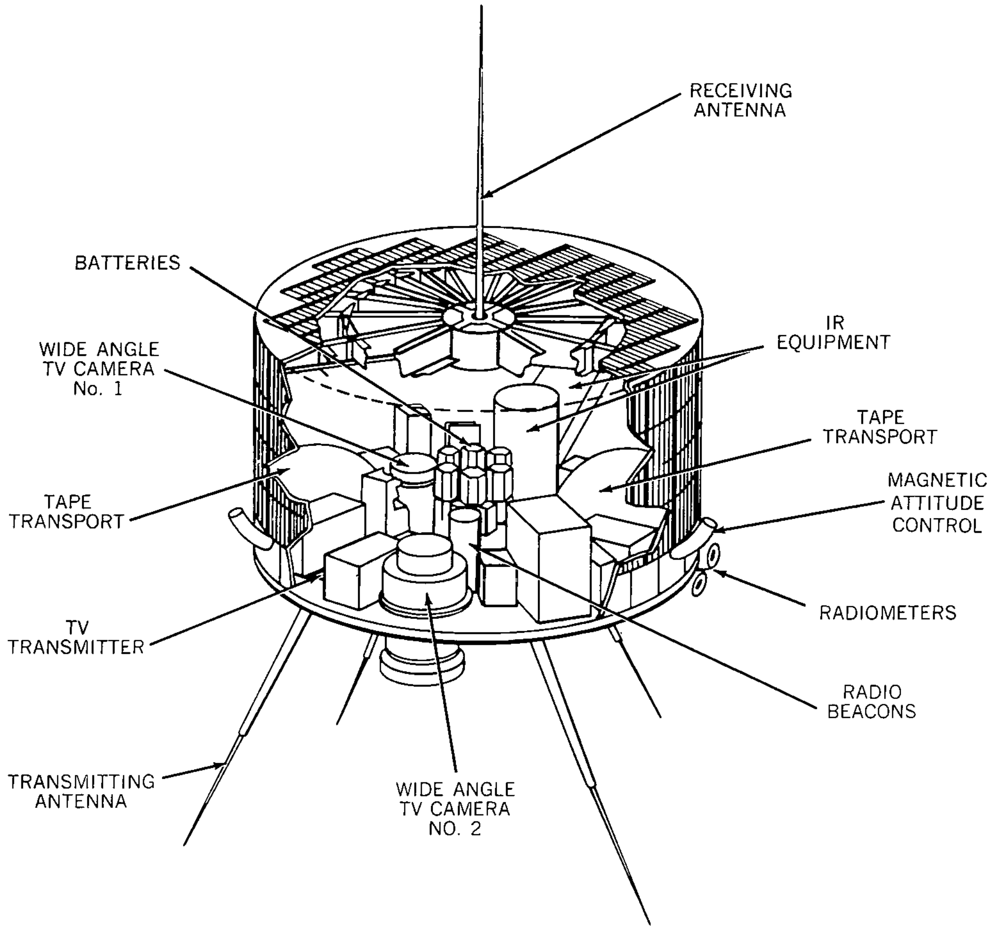


Figure 1—The Tiros III Satellite.

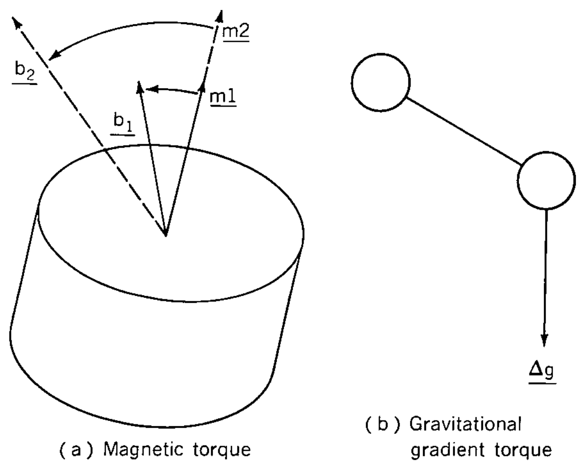


Figure 2—Torques acting to change satellite spin axis direction.

One of the major problems in Tiros is the movement of the satellite's axis because of torques. Figure 2 shows the torques acting to change the axis. The magnetic attitude control consists of a coil of wire around the pillbox's perimeter. Axis changes are achieved by varying the current flowing through this coil.

The axis direction must be known in order to interpret the photographs and sensor messages. Figure 3 shows the changing length of earth and sky transit times as the satellite moves. As the zenith angle changes, the pulse duration changes.

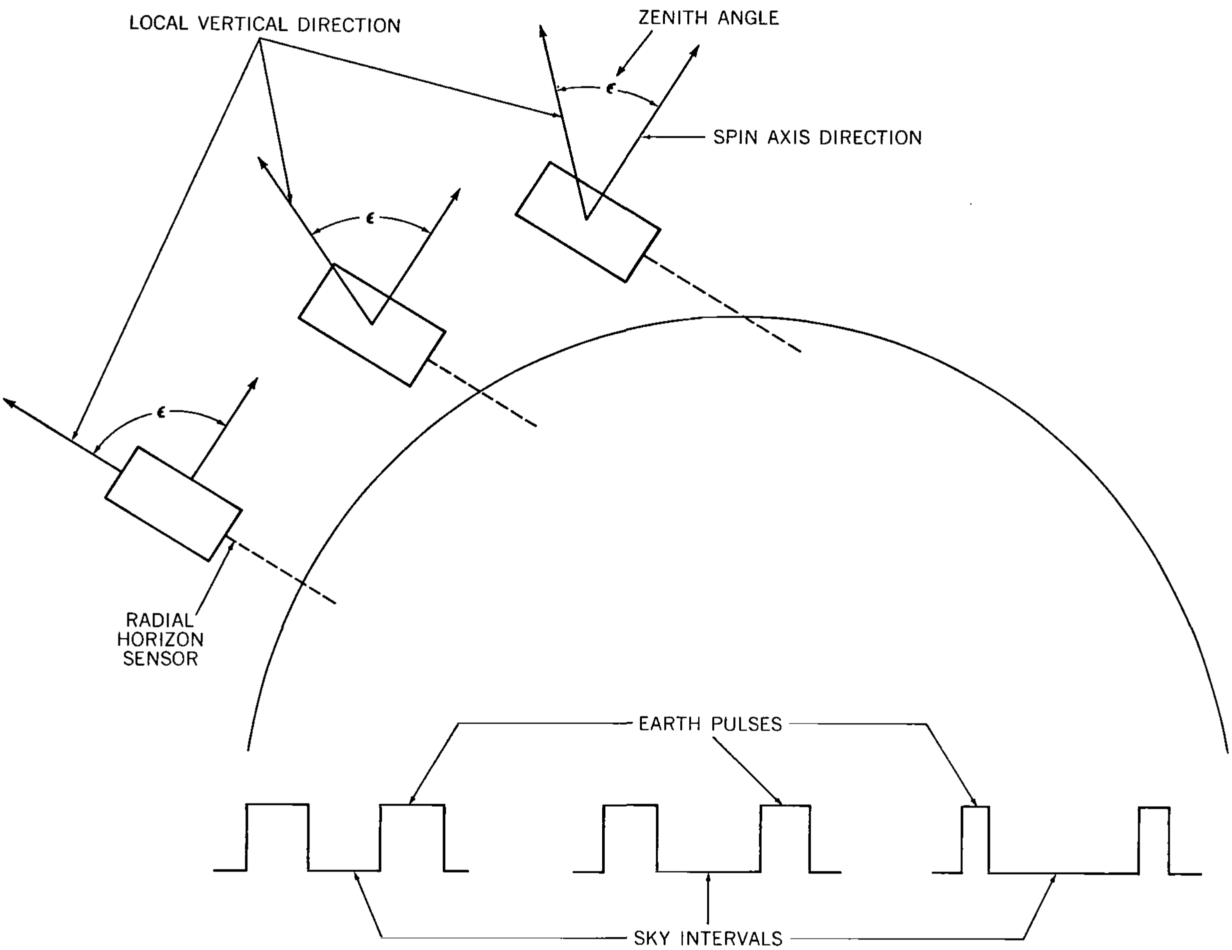


Figure 3—Relation between zenith angle and earth and sky intervals.

PROCESSING THE DATA TO DETERMINE SATELLITE'S ATTITUDE

Part of the raw data used in satellite attitude determination comes from the Horizon Sensor (H1) which is mounted at 90 degrees to the spin axis. The Horizon Sensor messages are received from the satellite only when it is within the range of the acquiring antenna. These messages therefore vary in length from 8 to 15 minutes. The pulses of varying length are received—unlabeled as to origin (earth or sky). As can be seen from Figure 3, we must know when to take pictures.

The sensor observational data are run through an *Edit Program,* (Figure 4a) which tests for true start and end times by counting all pulses, checks earth and sky scans to see if they fall within specific tolerances of an average spin rate for the satellite, and determines whether each pair is within the individual ΔT tolerances. Any pair of earth or sky scans not meeting a specified criteria is discarded in this process. Trend checking may be applied to the readings; however,

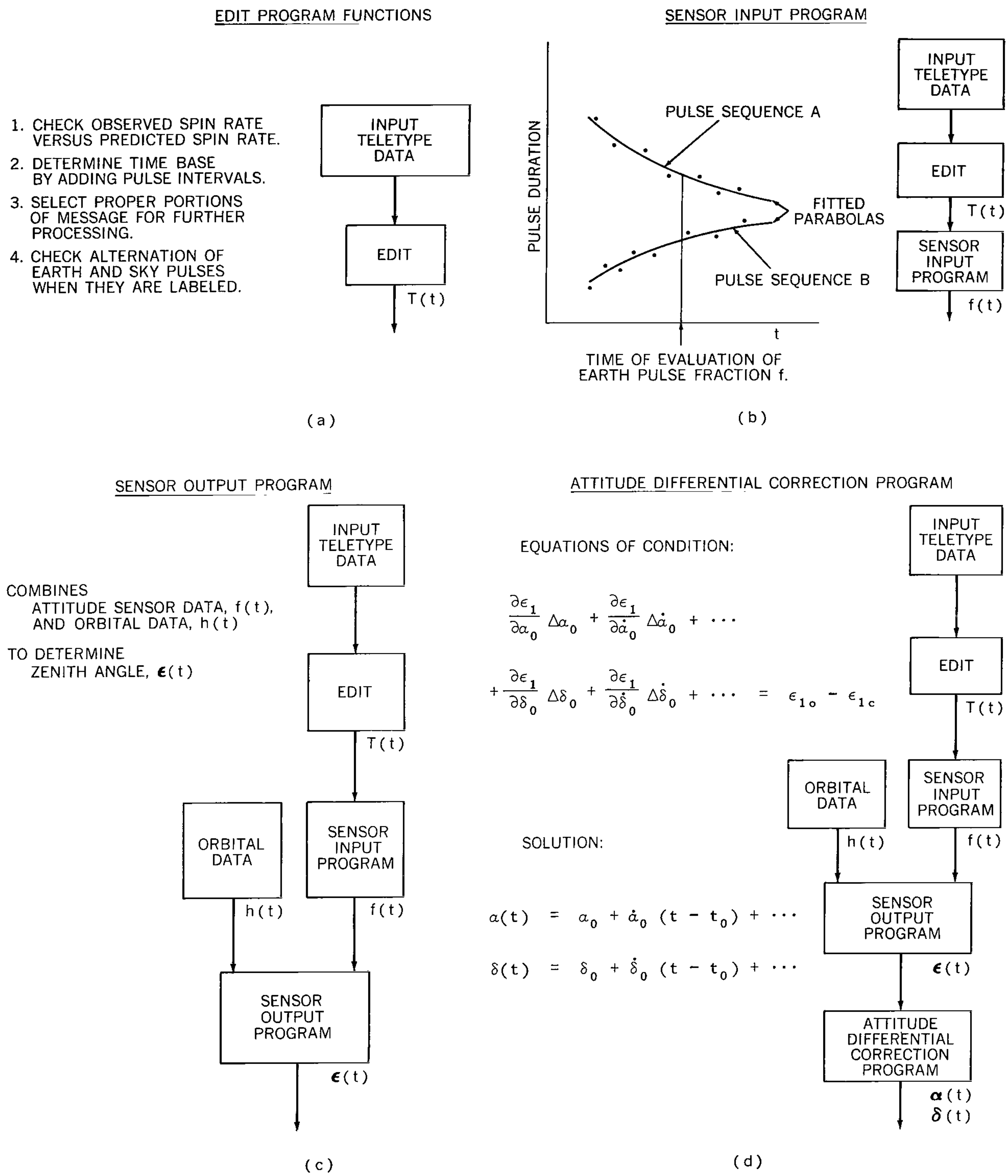


Figure 4—Data processing to determine satellite attitude.

the oscillations of earth readings are sufficiently severe that we require only a certain increase or decrease within a specified tolerance. Checks and diagnostics are made throughout the message.

The *Sensor Input Program,* (Figure 4b) uses the output of the Edit Program to determine smoothed ratios of the time the sensors observe the earth to the time of one revolution of the satellite about its axis. Parabolas are fitted to the data; data points and parabolas with large standard deviations are eliminated.

The *Sensor Observation Program,* (Figure 4c) combines these fractions and orbital position tape data to produce corresponding zenith angles. Thus the zenith angles are determined from the sensor data and the precise orbital information.

The zenith angle data are used in the *Attitude Differential Correction Program* to determine right ascension and declination of the spin axis. This program uses analytic expressions for the partial differential correction coefficients and is intended for use over relatively short time intervals during which the axis motion can be represented by simple functions.

A standard iterative differential correction process is used until convergence is achieved and a solution found. This process, which also eliminates data differing greatly from the predicted values, is a third occasion for removing inconsistent data.

The *Attitude World Map Program,* (Figure 5) calculates a minute by minute attitude map, which shows favorable picture taking areas based on optimal sunlight and angle criteria and numerous other quantities. This in both magnetic tape form and book form is widely used by the TIROS Technical Control Group, and the Weather Bureau meteorologists to command the satellite, to analyze the pictures and, ultimately to produce the radiation maps.

Figure 6 shows the pulses received from a different type of sensor—the infrared sensor (I2)—which is an open end tube mounted at 45 degrees to the axis. It illustrates one of the major difficulties in the system. The labeling of the sensors and the transitions from 2 pulse to 4 pulse areas required extreme care in establishing machine criteria. The two and four pulse areas depend on the satellite's orbital position (i.e., in some cases only one end of the open tube IR sensor views the earth and in other cases both the top and bottom of the open IR sensor view the earth).

PROCESSING IMPROVEMENTS

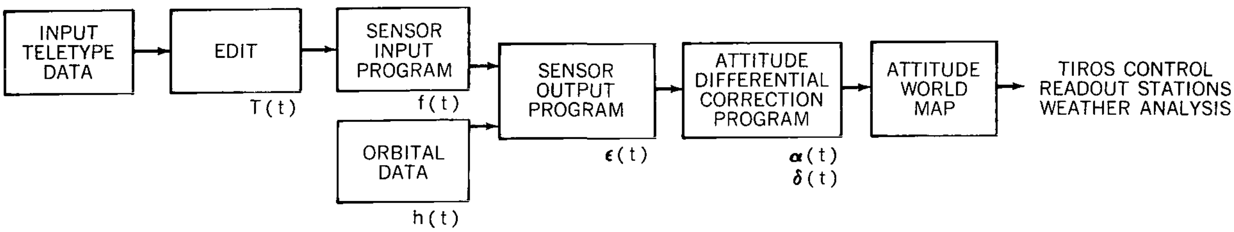
For ideal data, the process is straightforward. In the presence of noisy data which are frequently encountered, special care must be used. The large volume of data, about 10,000 points per day over a lifetime of 100 days or about one million points, accentuates the need for automation with machine logical decisions to eliminate bad data. Such logical decisions are difficult to program for a computer.

This problem is illustrated for one orbit of Tiros II in Figure 7. The two sensors should give the identical zenith angle for like times. The gap shown (of about 3 to 7 degrees) has caused a reexamination of data and methods. The effect of different bias levels in changing the earth pulse intervals is shown in Figure 8. The present system involves manual bias settings to cut off the sensor rise time. Work is now underway to have the computer do this by using the raw data to establish the proper bias setting.

BURST PASS NO. 191

	TIME			SATELLITE			PICTURE CENTER			PICTURE BOUNDARY				PIC. TO SUN		PIC. TO SAT.		STATION TO SATELLITE					
	DAY	HOUR	MINUTE	LATITUDE	LONGITUDE	ALTITUDE	LATITUDE	LONGITUDE	SLANT RANGE	LATITUDE	LONGITUDE	LATITUDE	LONGITUDE	ELEVATION	AZIMUTH	ELEVATION	AZIMUTH	NUMBER	RANGE	AZIMUTH	ELEVATION	NADIR ANGLE	SUN ANGLE
	6	10	7	4.8	200.6	624	NO INTERSECTION																
	6	10	8	7.6	202.8	623	NO INTERSECTION																
	6	10	9	10.4	205.1	622	NO INTERSECTION																
	6	10	10	13.2	207.4	622	NO INTERSECTION																
	6	10	11	15.9	209.8	621	NO INTERSECTION																
	6	10	12	18.6	212.3	621	NO INTERSECTION																
	6	10	13	21.3	214.8	622	NO INTERSECTION																
	6	10	14	23.9	217.4	622	NO INTERSECTION											3	2661	250.9	2.1		
	6	10	15	26.5	220.2	623	NO INTERSECTION											3	2284	253.9	6.2		
	6	10	16	29.0	223.0	624	NO INTERSECTION											3	1918	258.1	11.0		
	6	10	17	31.4	226.1	626	NO INTERSECTION											3	1570	264.4	17.2		
	6	10	18	33.7	229.3	627	NO INTERSECTION											3	1261	274.6	25.0		
	6	10	19	35.9	232.7	629	NO INTERSECTION											3	1024	293.0	34.4		
	6	10	20	38.0	236.2	631	NO INTERSECTION											3	920	323.9	40.4		
	6	10	21	40.0	240.0	633	NO INTERSECTION											3	991	356.7	36.4		
	6	10	22	41.8	244.0	636	NO INTERSECTION											3	1206	17.5	27.3		
	6	10	23	43.5	248.3	638	NO INTERSECTION											3	1505	29.1	19.1		
	6	10	24	44.9	252.8	641	NO INTERSECTION											3	1845	36.1	12.7		
	6	10	25	46.2	257.5	644	NO INTERSECTION											1	2577	295.2	3.5		
																		3	2207	40.6	7.7		
	6	10	26	47.2	262.4	646	NO INTERSECTION											1	2227	299.8	7.5		
																		3	2581	43.9	3.5		
	6	10	27	48.0	267.5	649	NO INTERSECTION											1	1896	306.1	12.2		
	6	10	28	48.6	272.7	652	NO INTERSECTION											1	1599	315.2	17.7		
	6	10	29	48.8	278.0	656	NO INTERSECTION											1	1357	328.8	23.7		
	6	10	30	48.8	283.3	659	NO INTERSECTION											1	1207	348.3	28.6		
	6	10	31	48.6	288.6	662	NO INTERSECTION											1	1184	12.1	29.7		
E	6	10	32	48.0	293.8	665	41.0	277.9	1698	N.I.		N.I.		22	100	16	52	1	1295	33.7	26.0	100	81
E	6	10	33	47.3	298.9	668	42.2	284.9	1467	N.I.		N.I.		17	104	21	58	1	1510	49.3	20.3	97	83
E	6	10	34	46.2	303.7	671	42.6	291.3	1310	N.I.		N.I.		13	108	25	63	1	1791	59.8	14.7	94	85
E	6	10	35	45.0	308.4	674	42.4	297.4	1194	N.I.		N.I.		8	112	29	68	1	2111	66.9	9.9	91	87
E	6	10	36	43.6	312.8	677	41.7	303.1	1105	N.I.		N.I.		4	116	33	72	1	2454	72.0	5.7	88	89
E	6	10	37	41.9	317.1	681	40.7	308.4	1034	N.I.		N.I.		0	119	37	76	1	2810	75.9	2.0	85	92
E	6	10	38	40.2	321.0	684	39.4	313.4	976	N.I.		N.I.		3	123	41	79					82	94
E	6	10	39	38.2	324.8	687	37.8	318.1	928	N.I.		N.I.		8	126	44	82					79	96
E	6	10	40	36.2	328.3	690	35.9	322.4	888	N.I.		N.I.		12	129	48	84					76	98
E	6	10	41	34.0	331.7	693	33.9	326.5	855	N.I.		N.I.		16	131	51	86					73	100
	6	10	42	31.7	334.8	695	31.8	330.3	827	N.I.		N.I.		20	133	55	88					70	103

(a)



(b)

Figure 5—Attitude World Map Program.

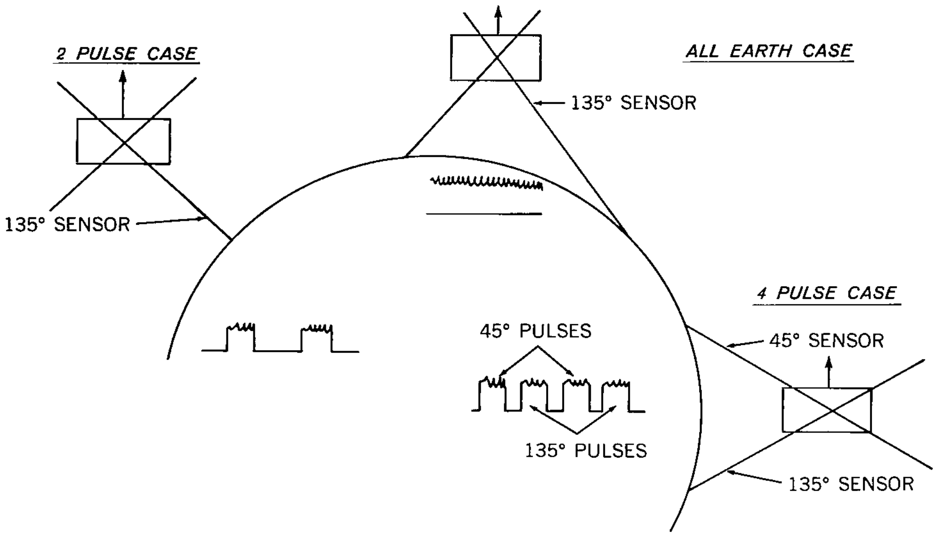


Figure 6—Infrared sensor data.

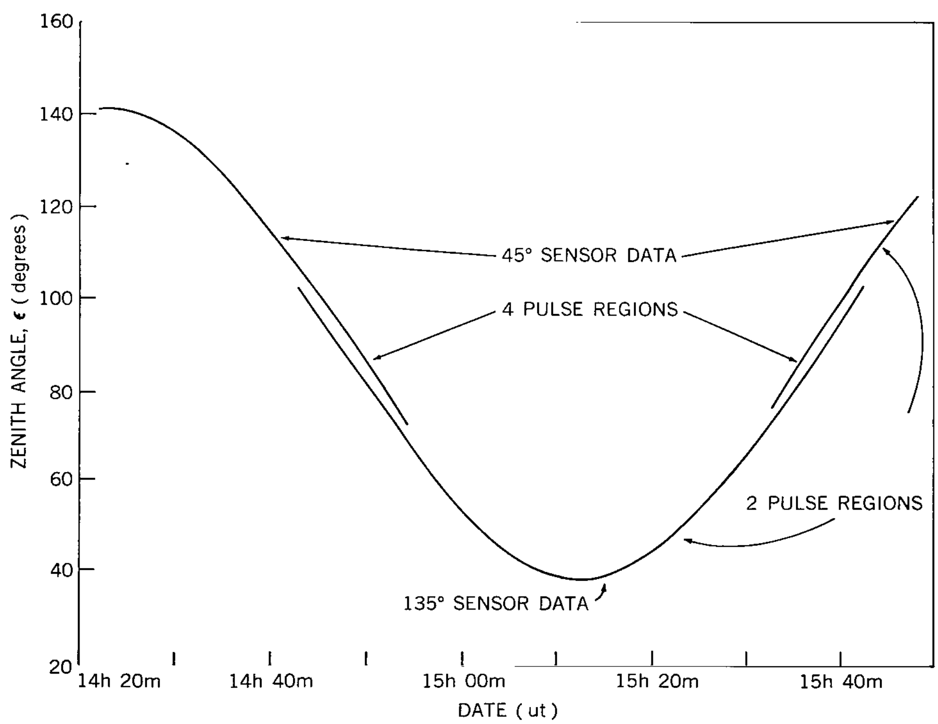


Figure 7—Orbit 362, Tiros II, December 18, 1960.

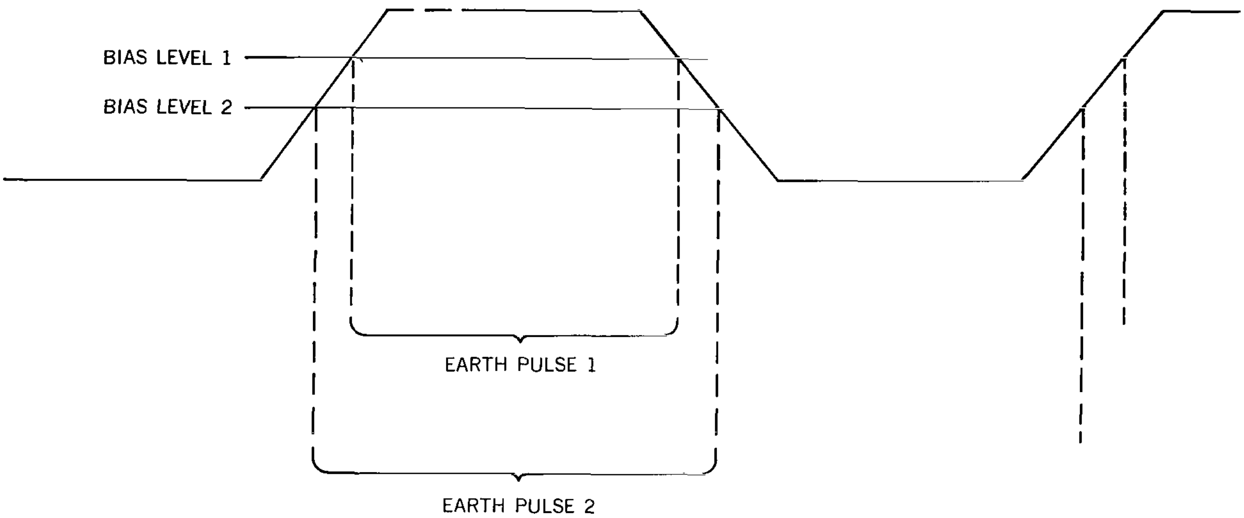


Figure 8—Effect of bias level on apparent earth pulse length.

The station picture observations are data points taken from gridded overlays; good pictures with identifiable landmarks yield data as to the latitude, longitude and time of the picture. Using the two vectors shown (Figure 9) the third one is obtained; lower California on a smoggy day is recognizable. Here the main problem is the accurate time of the picture-taking. An error in identification of one frame means an error of about 20 degrees in right ascension and declination.

Figure 10 shows the theoretical path with the laboratory magnetic moment and the actual path taken by Tiros III. Accurate measurements of the satellite's magnetic moment were made and the path should have been as shown. After much work and artificial changes (see Table 1) in the moment, the computer calibrated the moment and found a solution.

The value of the magnetic moment determined by the computer program while the satellite was in orbit was significantly different (Table 1) from the value determined by means of laboratory calibrations of the satellite's magnetic moment. The scored values are actual measurements as calibrated by the computer. The most likely explanation of this difference appears that the changes in the satellite's magnetic properties are the effects of the launching shocks and vibrations upon the stray magnetism of battery cans and other materials (of miscellaneous value magnetically). This new value of the satellite's magnetic moment determined from the orbital and attitude data was sufficiently different from the value determined from the ground measurements to require redetermination of the ground command program which had been established for the satellite's steering electromagnet.

Referring to Figure 10 which shows the deviation from the actual path, we note that Figure 2 also illustrates the change in satellite axis direction as the magnetic moment along the axis is changed. A theoretical model was developed which accounts accurately for the effects of the earth's gravitational gradient torques, the torques due to the satellite's magnetic moments—including those induced by the electromagnet and the eddy current torques. An expression

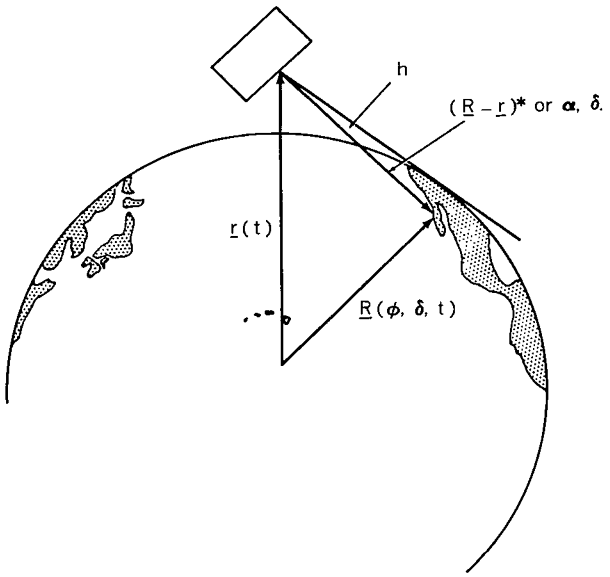


Figure 9—Determination of spin axis direction from television picture data.

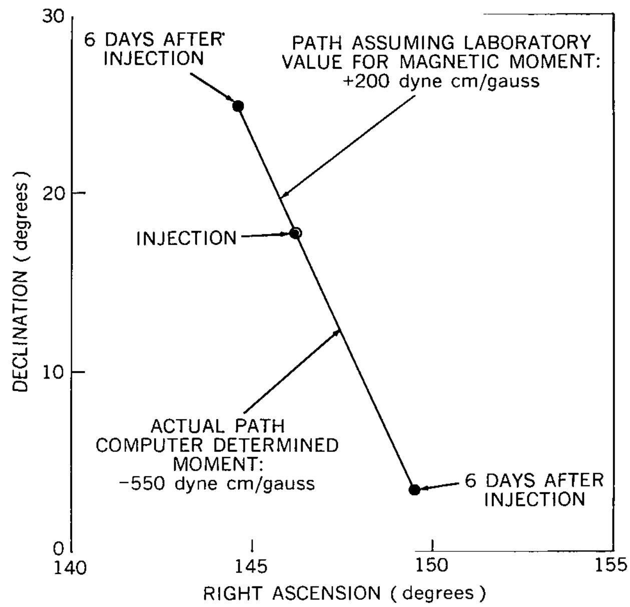


Figure 10—Tiros III.

Table 1

Measurement of the axial component of magnetic moment.

Satellite	Value of Axial Component (dyne-cm/gauss)				Difference between Laboratory and Mgap values (dyne-cm/gauss)
	Laboratory		Mgap Program		
	Sunlit	Dark	Sunlit	Dark	
Tiros I			-696*	-884*	
Tiros II	103 ± 50	-320 ± 50	-297**	-720**	-400
Tiros III	330 ± 50	0 ± 50	-420**	-750**	-750

* Sunlit-dark difference determined by Mgap program.
**Laboratory value for sunlit-dark difference assumed.

containing about two dozen terms was used to represent the earth's magnetic field. The position of the satellite in this magnetic field and in the gravitational field was determined on the basis of the precise Minitrack orbit.

This model has been programmed and is used to steer the satellite by changing the moment artifically. The data used for the magnetic and gravitational attitude program (MGAP) are:

1. Satellite positions based on precise minitrack orbit;

2. Earth's magnetic field based on Finch and Leeton's harmonic coefficients;
3. Spin rate based on computer program results;
4. Satellite moments of inertia based on laboratory measurements; and
5. Satellite magnetic moments
   a. Eddy current, based on spin rate decay data
   b. Steering electromagnets, based on laboratory calibrations and telemetered switch positions.

The telemetered switch positions have been another source of difficulty, especially in Tiros II. Some switch changes occurred inadvertently when no reliable time could be associated with the event. This model and program were applied to determine the most likely time and the proper switch position. The parameters that can be determined are:

1. $\alpha(t)$;
2. $\delta(t)$;
3. Axial component of magnetic moment in sunlight; and
4. Axial component of magnetic moment in dark.

One of the most important uses of the model is to steer the satellite. Figure 11 shows the criteria used to limit the angle between the axis and the sun's direction. The steering criteria are designed: (1) To keep the sun away from the sensors and the cameras (top and bottom of the satellite); (2) To keep the maximum zenith angle about 20 degrees to assure good pictures for horizon angle measurement; and (3) To keep the right ascension and declination within certain tolerances with reference to the sun's right ascension and declination. Figure 12 shows the predicted and

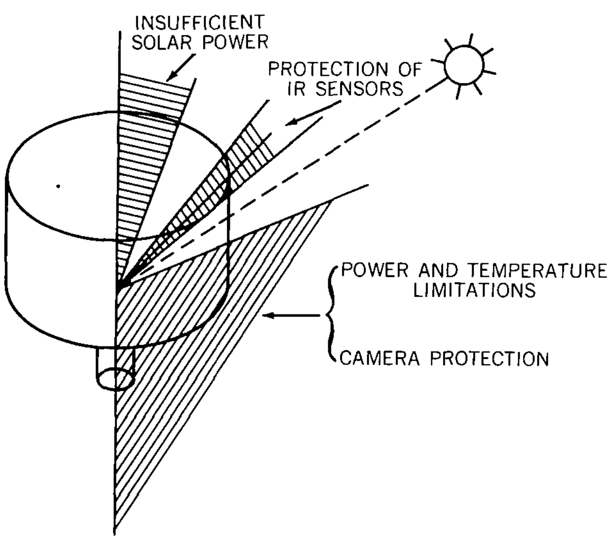


Figure 11—Limitations on angle between satellite axis and direction toward sun.

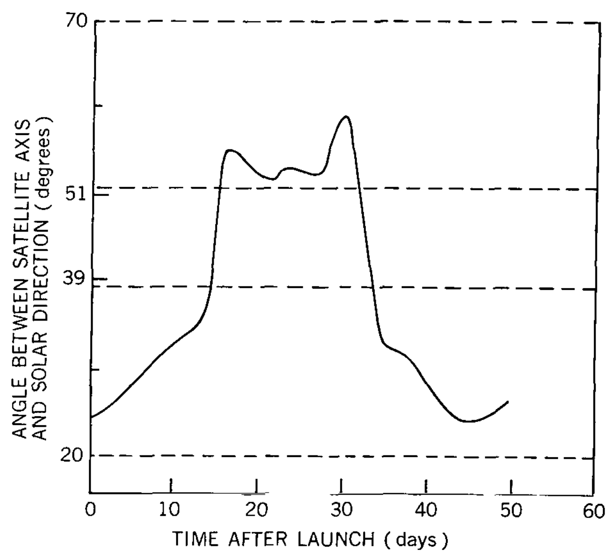


Figure 12—The predicted and differentially corrected sun axis angle.

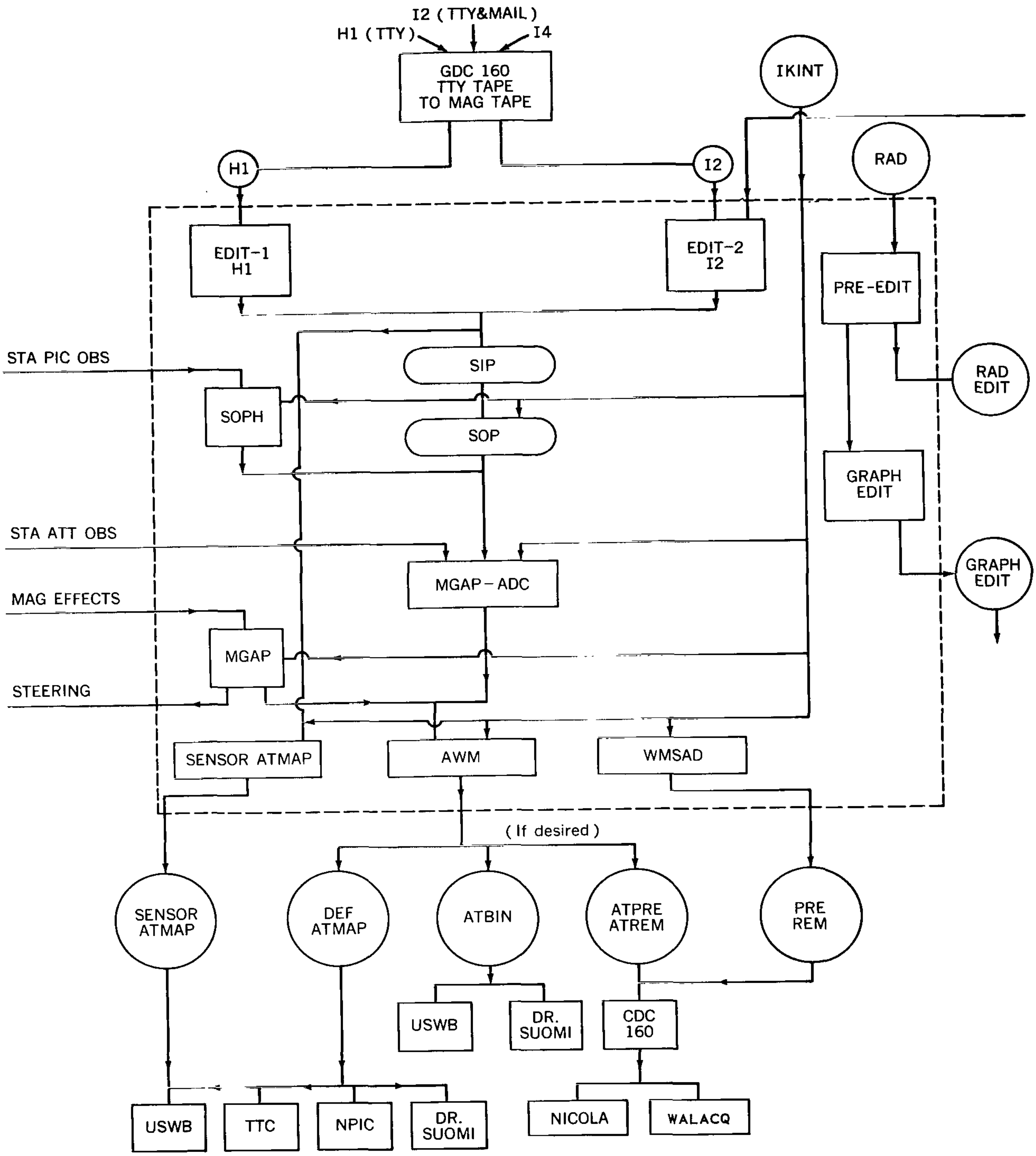


Figure 13—Tiros data flow chart.

differentially corrected sun axis angle. To meet the criteria, the sun axis angle must be from 20 to 39 degrees or from 51 to 70 degrees. To avoid damage to the instruments and experiments, two days or less should be spent in the 0 to 20 degree, 39 to 51 degree and over 70 degree regions. Obviously, all of the criteria cannot be satisfied simultaneously but an optimized set can be achieved.

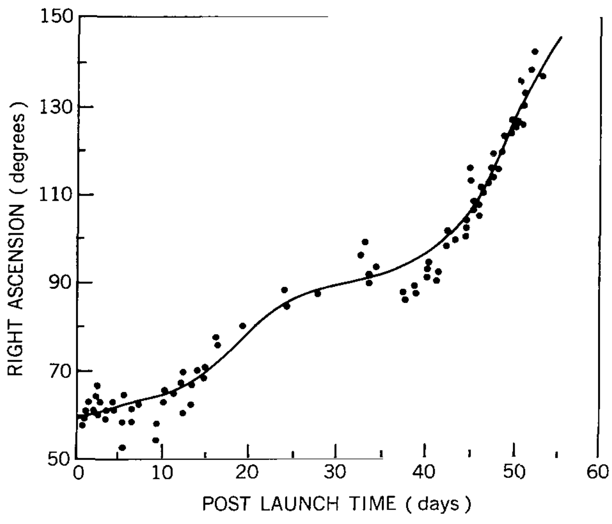
CONCLUDING REMARKS

The uses made of the MGAP program are summarized as follows:

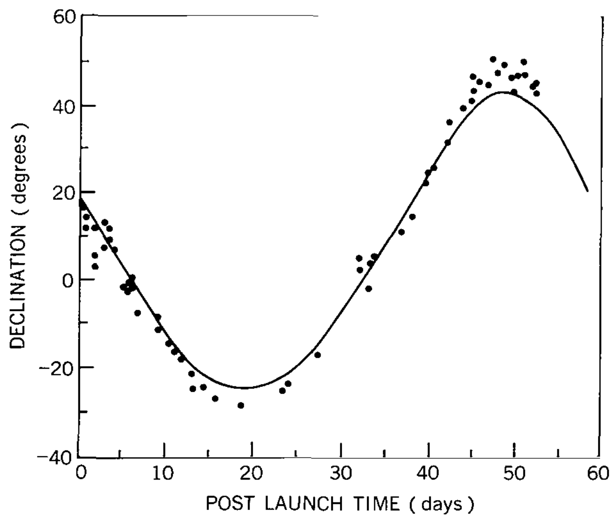
1. *Definitive determination of satellite attitude;*
2. Long range prediction of satellite attitude;
3. Determination of satellite steering program; and
4. Determination of axial components of magnetic moment in sunlight and in dark.

Each of these has been quite important in the Tiros program and represents a contribution to space research and development. The entire system (Figure 13) contains some 42,000 machine instructions, mostly in FORTRAN language, and is quite comprehensive and flexible in the variety of observational data which can be used.

Tiros I did not contain the steering mechanism described previously. However, the results obtained from the theoretical model after the in-flight calibration by means of the computer of the magnetic moment are shown in Figure 14. The points shown represent the most carefully determined right ascension and declination from "bench mark" quality photographs. The curves shown



(a) Right Ascension



(b) Declination

Figure 14–Tiros I spin axis.

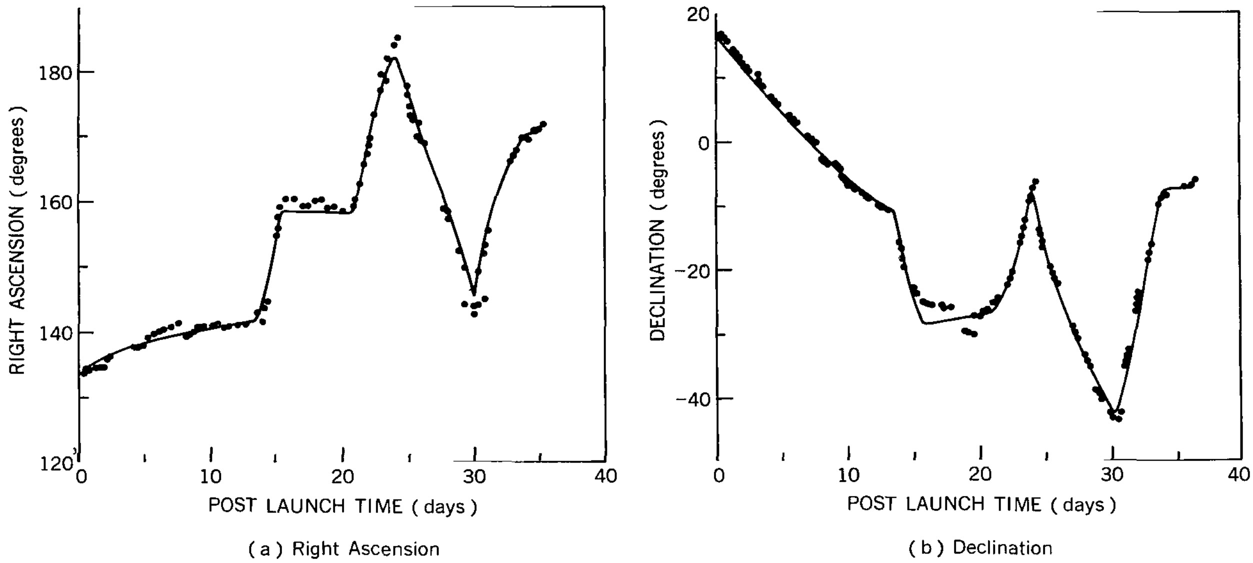


Figure 15—Tiros III spin axis.

represent the single theoretical model differentially corrected over a time interval of 56 days after which time spin up occurred. This is the first definitive attitude for a satellite of this type.

Tiros III, however, did contain the steering electromagnet. Results using the differentially corrected model are shown in Figure 15. Work is now underway to resolve some of the difficulties. Uncertainties in time and angular measurement have necessitated special care and logic in the programs. In addition, the triggering of the sensors going from earth to sky scans has been handled by a rather subjective method. A new approach which will have the computer calibrate the best sensor bias level and produce better attitude data is being programmed. It should remove many of the present difficulties and yield more accurate attitude data.

The results obtained using this system have been good; and the computer is being used: (1) To determine the axial components of the magnetic moment; (2) To determine a steering program; (3) To make long range attitude predictions; and (4) To determine the definitive attitude.

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NASA-Langley, 1964 G-530

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